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TITLEEXOSKELETON INTERFACE APPARATUSField of the invention

The present invention relates to an exoskeleton interface apparatus.

5 In particular, the invention relates to an exoskeleton haptic interface apparatus capable of engaging directly with a user, detecting the motion of limbs and reflecting sensations of force to predetermined areas of contact.

Background of the invention

10 As known, a variety of types of exoskeleton apparatus exist for measuring the position and/or the orientation of an user's limb and that can reflect a force feedback at determined points. As force feedback is meant the replication on the user of "haptic" sensations  
15 reflecting handling forces of real or virtual objects.

If the objects are real and the user interacts directly with a physical environment, then Teleoperation is involved, whereas if such objects and the whole environment are created by computers using electronic  
20 displays, than Virtual Reality is involved.

Teleoperation provides bilateral communication between a manipulator (robot) operating in a remote environment (slave) and an interface apparatus (master) controlled by the user. This allows to give the robot the capacity of  
25 carrying out not foreseeable high skill operations on not structured objects and environments, i.e. whose shape, size and spatial disposition are unknown a priori.

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Furthermore, since the master and the slave can communicate even if located at considerable distance (for example by means of satellite broadcasting) operations can be carried out in absolutely safe conditions at places  
5 that are dangerous to humans, such as in the maintenance of nuclear sites or of satellites.

Virtual reality can be defined as an interactive and immersive experience in a simulated environment. The fields of application of Virtual reality are many. Among  
10 them the following can be cited: simulation, training, medicine, entertainment, teaching, design, etc.

A variety of exoskeleton interface apparatus exist for upper limbs of humans.

For example, a first type of interface apparatus that  
15 is used as master in a teleoperation system is "Arm Master" of Sarco Inc. It has 10 freedoms (arm + hand) and is capable of reflecting a force on 3 fingers. The actuating system is hydraulic so that it has the advantage of having a high passband, but it has the drawback of  
20 having a big encumbrance and a low "transparency of use" (high friction and high reflected mass on the user).

Then, a type of exoskeleton exists with parallel kinematics developed by the Korea Institute of Science and Technology. The choice of a parallel kinematics has the  
25 advantage of a good stiffness, but the mobility of the shoulder and of the elbow are limited. Six linear actuators are provided (three for the arm and three for the forearm) using DC motors and ball recirculations. This solution reduces the reversibility rate and then the

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transparency of use of the device.

Furthermore, Southern Methodist University obtained a pneumatically actuated interface apparatus with four freedoms called "the Haptic Arm". In this case the  
5 sensorisation is obtained by pressure sensors and linear position transducers. The device even if compact and light, is characterised by a low stiffness owing to the pneumatic actuation.

Normally, in the above systems the physiological axes  
10 of the arm, forearm and wrist do not coincide with the exoskeleton axes, with subsequent decrease of the actual workspace that is the intersection between the workspace of the human limbs and that of the robotic structure.

Finally, Hashimoto Lab. of Tokyo disclosed an  
15 exoskeleton with seven freedoms, wherein both the angle and the torque of each joint can be determined by a sensorisation system. The transmission of the movement is carried out by a gearing. This type of transmission allows the physiological axes to coincide with the mechanical  
20 axes, but with the drawbacks of high backlash and a low rate of reversibility. In addition, since the motors are arranged on the mobile parts, the inertia reflected on the user is remarkable. Problems of safety are also caused by the fact that, being the structure closed, the  
25 introduction and the extraction of the arm it is not simple and immediate.

#### Summary of the invention

It is therefore object of the present invention to provide an exoskeleton interface apparatus to be used as

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master in teleoperation systems or as interaction device with a virtual environment in virtual reality systems, which allows to detect the posture of a shoulder, of an arm, of a forearm and of a wrist and is capable of  
5 reflecting controlled forces in reaction to the movement of the user.

It is another object of the present invention to provide an exoskeleton interface apparatus in which the axes of the joints coincide substantially with the  
10 physiological axes of the human limbs in order to increase the actual workspace of the device.

It is a further object of the present invention to provide such a device that has minimum inertia and at the same time is equipped with high stiffness.

15 It is a particular object of the present invention to provide such a device that an user can put on and off easily.

These and other objects are accomplished by the exoskeleton interface apparatus for detecting the posture  
20 of a limb of an user and/or for reflecting controlled forces on the user, according to the present invention, whose characteristic is that it comprises:

- at least an element of interaction with an user defining a point of contact with the object to  
25 touch and/or to handle;
- a plurality of rigid links pivotally connected in series, between said element of interaction and a rigid fixed link, by means of rotational joints whose rotational axes coincide in operative

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conditions with the physiological axes of at least one limb of the user;

- means for generating a motive or braking force arranged in said rigid fixed link;
- 5 - means for transmitting said force to said rotational joints;
- means for measuring the angular position of said rotational joints.

Preferably, said rigid links comprise:

- 10 - said rigid fixed link, with function of base frame, operatively connected to a second rigid link by a first rotational joint having an axis of rotation;
- a third rigid link operatively connected to said second rigid link by means of a second rotational joint having axis of rotation orthogonal to the
- 15 axis of rotation of the first rotational joint;
- a fourth rigid link operatively connected to said third rigid link by means of a third rotational joint with axis of rotation orthogonal to the axis
- 20 of rotation of the second rotational joint;
- a fifth rigid link associated to said element of interaction operatively connected to said fourth rigid link by means of a fourth rotational joint.

In particular, if the exoskeleton interface  
25 apparatus is used for monitoring the motion of the shoulder, of the arm and of the wrist of an user the axes of the first, of the second and of the third rotational joint are incident to one another and coincide with the

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physiological axes of the shoulder, whereas the axis of the fourth rotational joint coincides with the axis of the elbow.

The element of interaction can be connected to the fifth rigid link by means of a fifth rotational joint, for example a ring, for measuring the rotation of the wrist with respect to the elbow.

Advantageously, said applied force is opposite to the free movement of said rigid link corresponding to the movement of a limb of the user.

Preferably, said means for generating a force are motors, for example "torque motors" with a high torque/mass ratio.

Advantageously, each rotational joint is brought independently into rotation about the respective axis, by one of said means for generating a force through said means for transmitting said force.

Advantageously, said means for transmitting the force created by said means for generating comprise at least one tendon. In particular, each means for generating said force is operatively connected to a respective rotational joint by at least one tendon.

Advantageously, since the rotational axes of the rotational joints lay in different planes a plurality is provided of means for deviating each respective tendon through said rigid links.

If said means for transmitting are tendons, said means for orienting can be idle pulleys arranged arbitrarily in the space. This solution is simple to carry out and

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assures a good stiffness and lightness, without backlash and low friction.

Advantageously, at least one joint of the exoskeleton interface apparatus has open geometry.

5        Preferably, the third rotational joint has open geometry. This solution allows to put on the interface apparatus easily with lateral movement, instead of introducing the arm into a closed bearing axially from the above, like in the devices of prior art. Furthermore, this  
10 solution allows to withdraw quickly the arm from the device in case of danger, increasing the safety of the apparatus.

Advantageously, on the axis of the first, third and fourth rotational joints is mounted an integrated  
15 epicyclic reduction gear for reducing the masses of the rigid links at the same conditions of stiffness and applied force.

Advantageously, said means for measuring the angular position of said rotational joints are mounted directly on  
20 the axis of said means for generating said force.

Preferably, said means for measuring the angular position of said rotational joints are incremental high resolution encoders.

#### Brief description of the drawings

25        Further characteristics and the advantages of the exoskeleton interface apparatus, according to the present invention, will be made clearer with the following description of an embodiment thereof, exemplifying but not limitative, with reference to the attached drawings,

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wherein:

- figures from 1 to 4 show in different perspective views an exoskeleton interface apparatus according to the invention from different angles for showing the different parts thereof;
- figures 5A and 5B show diagrammatically the arrangement of the motors and of the transmission parts that bring into rotation the first two rotational joints of the device of figures 1-4;
- 10 - figure 6 shows diagrammatically in a perspective view the spatial arrangement of the transmission parts of figures 5A and 5B.
- figures from 7 to 10 show a perspective view according to different angles of the exoskeleton interface apparatus of figure 1 put on an individual;
- figure 11 shows in a perspective view a possible embodiment of a motor for operating the rotational joints of the device of figure 1;
- figure 12 shows in a perspective view of a possible embodiment of a rotational joint with epicyclic reduction gear integrated used in the device of figure 1 for allowing the mutual rotation of two successive rigid links;
- 20 - figure 13 shows in a perspective view a possible embodiment of an open rotational joint used in the apparatus of figure 1.

#### Description of a preferred embodiment

In figures from 1 to 4 a possible embodiment is shown of an exoskeleton interface apparatus 1, according to the invention, for measuring the posture of the arm, forearm



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and wrist of an user and for reflecting controlled forces in predetermined areas of contact thereof.

As shown in said figures, the apparatus 1 comprises five rigid links 2-6 arranged in series capable of  
5 rotating reciprocally at the respective ends for monitoring angular movements of the arm, of the forearm and of the wrist of an user 60 and having at the tip an handgrip 30 for the user 60 same (figure 7-10) for reflecting a force feedback.

10 In particular, rigid links 2-6 can rotate at their ends by rotational joints 11-14, which have their rotational axes 31-34 incident in a point that is the intersection of the physiological axes of the shoulder.

More in detail, exoskeleton 1 comprises a rigid fixed  
15 link 2, or base frame, suitable for being anchored to a fixed plane, operatively connected to a second rigid link 3 at an end thereof through a first rotational joint 11 having an axis of rotation 31. Second rigid link 3 is then connected to a third rigid link 4 by means of a second  
20 rotational joint 12 with an axis of rotation 32 orthogonal to the axis of rotation 31 of first rotational joint 11. The presence of a fourth rigid link 5, which is connected to the third rigid link 4 by means of a third rotational joint 13 with an axis of rotation 33 orthogonal to the  
25 axis of rotation 32 of second rotational joint 12; allows to detect the motion of shoulder 61 of user 60. This is possible since the kinematics of shoulder 61 is approximated to a spherical joint with three degrees of freedom, and a measure of the angular movements of the arm

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is possible by causing the intersection point of the physiological axes of the shoulder 61 to coincide with the intersection of the axes 31-33 of the exoskeleton and by detecting the angular movement about each axis.

5 In the embodiment shown in figures from 1 to 4 a fifth rigid link 6 is also present associated to the handgrip 30 connected to fourth rigid link 5 by means of a fourth rotational joint 14 with axis of rotation coincident to the axis of rotation of the elbow of the  
10 user 60 (figure 7-10). In particular, handgrip 30 is connected to fifth rigid link 6 by means of a fifth rotational joint 15, for example a ring bearing, for measuring the rotation of the wrist with respect to the forearm.

15 With reference to figures 5A and 5B, where a kinematic diagrammatical view is shown of rigid links 2 and 3 respectively, the different rotational joints 11-14 are brought into rotation about the respective rotational axes 31-34 by means of motors 21-24, for example servo-motors  
20 such as torque motors (figure 11), with a high torque/mass ratio, and in particular, each motor 21-24 brings into rotation a single rotational joint 11-14 about the respective axis of rotation.

According to a preferred aspect of the invention,  
25 furthermore, all motors 21-24 are mounted on fixed base link 2, in order to minimize the mass of the parts in movement and the inertia that reflects on user 60.

Since rotational axes 31-34 of rotational joints 11-14 lay in different planes, a plurality of idle pulleys 50 is

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provided arranged arbitrarily in space (figure 6) for orienting tendons 41-44, which are the transmission means of apparatus 1, towards the respective rotational joints.

Each tendon 41-44, in substance, brakes the free  
5 movement of the relative rotational joint, according to signals responsive either to constraints on the slave apparatus in case of Teleoperation or to constraints of Virtual Reality. The braking tension is respectively transmitted by motors 21-24 to tendons 41-44 corresponding  
10 to the desired force on the joint. The tendons that lead to the most remote joints, in particular joints 13 and 14, go through the other rigid links and simply require more pulleys 50, suitably arranged.

This solution, even if very simple, assures a good  
15 stiffness and lightness, with low friction and without any backlash. Furthermore, the particular three-dimensional arrangement of the axes of the pulleys 50 allows to conform the apparatus 1 in a desired way, as close as possible to the human arm, in order to limit as far as  
20 possible the size of the apparatus and the interferences of the rigid links with respect to one another, as well as any interferences between the rigid links and body of the user.

For measuring the angular position of joints 11-14,  
25 for example, high resolution incremental encoders 51-54 can be used, which are available on the market, mounted directly on the axis of each motor 21-24. This solution allows to provide a "robust" and low cost sensorisation as well as to eliminate the passage of electrical tendons

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through mobile parts.

Each tendon 41-44 can be connected to each rotational joint 11-14 by either a single tendon branch, for a force feedback in a single direction or for only operating a  
5 brake in each respective rotational joint, or two branches parallel to each other, for a differential force feedback in two directions.

The detection of the angle of rotation of the shoulder 61 is carried out, according to the invention, by means of  
10 one of the three rotational joints, i.e. joint 13, with open geometry and shown in detail in figure 13. It provides substantially an open circular guide 102 on which a carriage 103 is slidably engaged, for example, by a ball recirculation mechanism. On carriage 103 a force is applied  
15 by the corresponding motor 23, through tendon 43, which brakes its free movement along open guide 102.

Such open geometry allows the user to put on the apparatus 1 laterally and in a very simple way (see figure 9) differently from exoskeletons of prior art, which  
20 instead provide the introduction of the arm through a circular closed joint. Furthermore, it assures the safety of the user which, in case of emergency, can withdraw the arm immediately.

The foregoing description of a specific embodiment  
25 will so fully reveal the invention according to the conceptual point of view, so that others, by applying current knowledge, will be able to modify and/or adapt for various applications such an embodiment without further research and without parting from the invention, and it is

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therefore to be understood that such adaptations and modifications will have to be considered as equivalent to the specific embodiment. The means and the materials to realise the different functions described herein could  
5 have a different nature without, for this reason, departing from the field of the invention. It is to be understood that the phraseology or terminology employed herein is for the purpose of description and not of limitation.

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